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A STATISTICAL COMPARISON OF UPLIFT DESIGN METHODS FOR AUGERED FOOTINGS IN SAND

C.B.H. Cragg and R.H.K. Tsang

Several methods for estimating the uplift capacity of augered footings in sand are evaluated. Using a data base of 217 load tests and a robust statistical approach, the accuracy of the eight methods are compared and ranked. The accuracy of different design methods vary depending on the relative density of sand ranging from loose, compact to dense. However, a single method providing the best overall capacity prediction was identified by a ranking procedure. A combination of methods providing superior performance is recommended.

1.0 INTRODUCTION

Predicting the uplift capacity of augered footings in sand is no simple matter because the failure surface changes shape with foundation geometry, soil shear strength and construction practice. Many methods have been proposed for calculating uplift resistance/1/. These methods include formulae based on a cylindrical shear surface/2,3,4,5/, on a truncated cone surface/6/ and on a curved shear surface/7/. Lateral earth pressure coefficients used in these formulae include the active case (Ka), the "at rest" case (Ko), the passive case (Kp) and the ubiquitous empirical uplift coefficient (Ku). Several sets of values have been proposed for the Ku factor alone/3,4,5,8/. With this variety of design approaches being proposed, it is not surprising that no single method is generally accepted. The Canadian Foundation Engineering Manual/9/ does not recommend a design method but rather advocates the use of load tests. Researchers at Cornell University, who currently lead the research by EPRI on this topic, favour design based on Ko, where Ko is measured by special field tests/10/. As measurements of Ko are not available to most designers, this latter approach may take some time to gain acceptance. No data base of foundation load tests, including in situ Ko test data, is currently available to evaluate this method.

A data base of 217 load tests in sand has been assembled where the soil properties are measured by conventional testing. The relative accuracy and consistency of eight design methods is assessed based on their ability to accurately predict the data base results. A description of the statistical

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analysis procedure used to rank the design methods is provided. The most accurate design methods are identified. In addition, the merits of using a single predictive method for design work versus using a combination of methods is discussed.

2.0 LOAD TEST DATA

In order to assess the various predictive theories, a large number of case histories of deep cylindrical foundations was assembled. Both full scale field tests and laboratory scale model tests are included. These foundations were installed in granular soils and tested to failure in uplift. The data set encompasses a broad range of foundation sizes, depth to diameter ratios, locations, testing agencies and soil strengths. A large portion of the data base came from sources described earlier/11/. This data has been supplemented with additional laboratory scale tests by Ontario Hydro/12/. In total, 217 load tests are employed in the data base. The division of these tests between field and laboratory scale and between soil density ranges is shown below:

Soil Density	Friction Angle	Scale of Load Tests		
		Field	Laboratory	Totals
dense	$>36^0$	22	84	106
compact	30^0-36^0	36	40	76
loose	$<30^0$	11	24	35
TOTALS		69	148	217

For consistency, the ultimate uplift loads applied were obtained from the load deflection graphs in the case histories. Soil strength data was used as reported in the case histories, but in some cases the background information did not permit validation of friction angle values. In a few cases, the measurements used to obtain the soil strength data were not reported.

3.0 METHODS OF PREDICTING FOUNDATION CAPACITY

The methods of predicting foundation uplift capacity are based on three different failure surface shapes: the cylinder, the truncated cone and the curved surface. Formulae for these surface shapes and the associated uplift coefficient values are provided in the following sections.

3.1 Cylindrical Shear Model

The general form of the equation used to predict the uplift capacity of cylindrical augered foundations, assuming a cylindrical failure surface, is:

$$Q = \frac{\gamma B D^2 \pi K \tan \phi}{2} + W \qquad \text{.....(1)}$$

where γ is the soil density
B is the foundation width
D is the foundation depth
W is the foundation weight
ϕ is the angle of internal friction for the soil
and K is the uplift coefficient.

This general formula is employed in six of the eight design methods examined in this review. These six methods differ only in the value of uplift coefficient employed. Conventional Rankine earth pressure coefficients are assumed to equal the uplift coefficient (K) in the first three design methods/2/. These values are Ka, Ko and Kp where

$$Ka = \frac{1 - \sin \phi}{1 + \sin \phi} = \text{active earth pressure} \qquad \text{.....(2)}$$

$$Ko = 1 - \sin \phi = \text{"at rest" earth pressure} \qquad \text{.....(3)}$$

and $$Kp = \frac{1 + \sin \phi}{1 - \sin \phi} = \text{passive earth pressure} \qquad \text{.....(4)}$$

In the next three methods, the uplift coefficient is designated Ku with the values provided by (a) Meyerhof (1973) as shown in Figure 1,
(b) Cragg et al (1985) as shown in Figure 2 and
(c) Meyerhof and Adams (1968) as shown in Figure 3.

The original work by Meyerhof and Adams/5/ combined theory with an empirical approach. Meyerhof/3/ later revised the work to cover oblique loading and Cragg et al/4/ recalculated the Ku factor using 160 case records and a statistical approach. A comparison of the original and most recent values of Ku is shown in Figure 4. For reference, the values of Ku recommended for corporate practice/8/ are shown in Table I.

3.2 Truncated Cone Model

For a truncated cone failure surface, the uplift capacity is given by:

$$Q = \gamma B D^2 \pi \, (M_\phi + M_\gamma) + W \qquad \text{.....(5)}$$

where $(M_\phi + M_\gamma)$ is a dimensionless coefficient related to soil properties ϕ and γ, having values given in Figure 5. These values are obtained from the formula:

$$(M_{\phi} + M_{\gamma}) = (M_{\phi_0} + M_{\gamma_0})(1 - \frac{1}{3}\frac{D}{R}\tan\alpha) \quad \text{.....(6)}$$

where $(M_{\phi_0} + M_{\gamma_0}) = \dfrac{\sin\phi\cos(\phi + 2\alpha)}{2\cos^2\alpha}$ for $0^0 < \phi < 50^0$ ..(7)

$R = \frac{B}{2}$ = foundation radius

and $\alpha = -\frac{\phi}{8}$ = angle of conical shear surface (Figure 5).

This model assumes friction is mobilized along the shear surface due to the active earth pressure coefficient/6/.

3.3 Curved Shear Model

In the curved shear surface failure model, passive earth pressure conditions are assumed to exist and a two dimensional analysis is used/7/. Foundation uplift capacity is given by:

$$Q = \gamma BD^2(M_{\Phi R}) + W \quad \text{.....(8)}$$

where $M_{\Phi R}$ is a dimensionless coefficient related to the soil property ϕ and having values given in Figure 6.

Comparing the theories, one finds that the uplift coefficient used in the first three theories is defined by soil strength alone. In the remaining five theories, the coefficient varies with both soil strength and the foundation depth to width (depth to radius) ratio. The latter theories differ in the value of earth pressure and the shape of shear failure surface assumed.

4.0 APPROACH TO EVALUATING THE DESIGN METHODS

The accuracy of the design methods was assessed by using the ratio of the predicted to the observed uplift capacity. This ratio was calculated for each of the 217 case histories and each of the 8 design methods. Using these ratios for comparison, the design method giving the best prediction would have an average ratio value close to one and a small range of ratio values around one. As straight numerical comparison of ratios does not fairly compare formulae which underestimate (ratios between zero and one) with formulae which overestimate (ratios between one and ten), the log of the ratio was used. Since the log function is symmetrical about the value 1.0, ratios requiring the same correction to reach one were equally valued. The statistical computer program Statgraphics ^{R} was used to obtain the median, range and outliers for each set of ratios. This approach imposes no probability distribution on the data analysis and is therefore free from any errors imposed by an incorrect distribution selection. The data analysis is presented in a graphical form,known as a notched box-and-whisker plot, where the notch represents the 95% confidence interval for the median value. Data

sets with overlapping notches are interpreted as having the same median value. Where data sets have the same median, the accuracy of the predictive equation is then based on the data set with the smaller range. An analysis of the outliers reveals whether unrepresentative points result from the theory or "poor" data.

As mentioned earlier, the data base contained both laboratory and field load tests. The laboratory and field data sets for a given predictive method can be combined into a pooled data set if the median values are the same. The predictive methods were then ranked according to the data set having the median ratio nearest to zero (log 1 = 0) and the smallest range. Rankings are given for the predictive methods within each soil density range (ie loose, compact, and dense). Overall accuracy of each method was assessed by summing the rankings across the three density ranges and comparing the summed rankings.

5.0 RESULTS

Forty-eight notched-box-and-whisker plots were prepared to determine if field and laboratory data could be combined. A comparison of the median values of these plots (Appendix A) showed that 19 of the 24 separate data sets (3 density ranges times 8 design methods) had comparable median values for field and laboratory tests. Median values that were not comparable occurred for Ka and Ko in dense soil and for the truncated cone and curved shear theories in compact soil (Table II). As the majority of data groups had comparable median values, field and laboratory data were combined for the remaining analyses. Median values for loose, compact and dense soil density ranges were not comparable so the data from different density ranges could not be combined.

Table III shows the median values of the combined data sets for each of the eight theories and three density ranges. The supporting notched-box-and-whisker diagrams are contained in Appendix B. Remembering that the data represents the log of the ratio of predicted to actual foundation capacity so that a value of zero is being sought, Table III shows that no single theory accomplishes the best prediction (ie value closest to zero) across the three density ranges. In the loose range, Ko is the best predictive theory. Ku (1985) followed by the truncated cone are the next best predictors of actual load. The order of ranking these latter two theories was based on an examination of the range of ratio values. Ku (1985) had the smaller range. The rankings of all the theories are listed in Table IV. In the compact range, the best prediction is obtained by the truncated cone method followed closely by the three Ku methods. Ku (1985) again ranks second. In the dense range, the three Ku methods give the best prediction. On the basis of median values, these three methods are equally good. When the scatter of predictions is taken into account, Ku (1968) ranks first, Ku (1985) places second and Ku (1973) is rated third (Table IV).

Further examination of Table III shows that, in the loose range, the first ranked theory (Ko) tends to be slightly conservative on average and has a range of values that is skewed towards conservative estimates but that does extend into the unconservative area. On a linear scale (Table V), Ko gave estimates ranging from 0.35 to 1.58 times the actual uplift test values. The median value of 0.71 can be seen to be the closest value to 1.00 for

predictions in loose soil. From Tables III and V, it can be seen that the second most accurate predictive theory, Ku (1985), has an unconservative median value and a range that is skewed towards unconservative values.

In the compact range, the truncated cone method has been rated first. However, the choice between this theory with the most accurate median value and any of the Ku theories with marginally less accurate and less conservative median values but smaller more conservative and more reliable ranges is less clear cut than in the loose soils.

In the dense range, the Ku theories are clearly superior, having the most accurate median predictions of any theory in any density range. In addition, these three versions of the Ku theory have a small range of values that is well balanced between conservative and unconservative results. The difference between range values and the subsequent rankings of these theories is quite small, as seen in Table V.

Based on the rankings within each density range, a combined ranking was prepared (Table IV). The overall ranking obtained indicates that Ku (1985) and Ku (1968) would provide the best predictions across all density ranges if one theory was selected for all design work. A better overall ranking could be obtained by using a combination of theories in design work rather than using one theory alone. For example, using either Ku (1968) or Ku (1985) for the dense and compact ranges and Ko for the loose density range would yield a better overall ranking (and better predictions).

6.0 DISCUSSION

Examination of the ranking results in Table IV sheds some light on the factors that make a positive contribution to uplift capacity prediction. In loose density soils, the uplift coefficient (K) is dependent only on Ø and independent of foundation D/B ratio in all the design methods being examined regardless of the failure surface assumed. The results show rankings are scattered among the theoretical, empirical and failure surface approaches indicating no clear pattern other than, not surprisingly, the curved shear failure surface and passive earth pressure are least appropriate in this density range.

In the compact and dense density ranges, the design methods that use both Ø and D/B in selecting the uplift coefficient (ie Ku, truncated cone and curved shear) rank ahead of methods selecting the factor solely on the basis of Ø (ie Ka, Ko and Kp). This limited comparison indicates the current, empirically based cylindrical shear failure methods provide better estimates than the curved shear or truncated cone failure surface methods. If the field and laboratory data sets for the curved shear and truncated cone theories are used separately, the rankings are altered (see Table VI). (Remember, from Table II, that use of a combined data set was not legitimate for these theories in the compact density range.) Using field data would improve the rank of the curved shear theory and worsen the rank of the truncated cone theory but would not encourage one to favour either of these two theories over the cylindrical shear surface model. While the curved shear and truncated cone models should not be discarded based on an examination of only two examples of these models and in the knowledge that other, potentially more accurate formulations of

these models do exist/13,14,15/, more work is required to bring the accuracy of these theories to the level now being achieved with the cylindrical shear model and empirical Ku coefficients. The cylindrical shear model is recommended for current design work.

As a significant proportion of the data base used for this analysis was employed to create the factors for the Ku (1985) model, a check for biased results was undertaken. This check involved redoing the statistical analysis of this theory using 61 compact and dense laboratory data points/12/ that were not included in the (Ku) 1985 development work. The resulting log predicted to actual uplift capacity ratios, shown in Table VI and Appendix C, would worsen the rank of this theory in the compact range and leave it unaffected in the dense range. These changes would improve the rank of Ku (1968) on an overall basis. The recommendation to use Ku (1968) in combination with Ko for loose soils could only be strengthened by this change.

Selection of Ko for uplift design in loose soil has been advocated previously/16/. Combination of Ko for loose with Ku (1968) for compact and dense combines accuracy with computational simplicity and concept compatibility. These two theories are compatible because they are based on the same failure model. Computation is simple because, aside from the different K factors, these theories employ the same equation.

As mentioned above, a review of the outliers found by the statistical analysis was carried out. As seen in Tables VII and VIII, there are very few outliers in any data set and this number (less than four) is small compared to the size of the data sets (ranging from 35 to 106). The number of outliers is consistent from theory to theory. Data points identified as outliers occurred either at random (once only) or consistently (in several if not all theories). These facts indicate that generation of outliers is not attributable to any theory in particular but rather to the data points and their accompanying case histories. Further, the ranking established above is not sensitive to the presence or absence of outlying data points.

7.0 CONCLUSIONS

Eight methods for predicting uplift capacity have been reviewed for accuracy using statistical analysis and a data base of 217 load test case histories, with the following conclusions:

1. For most of the theories and density ranges examined, the results were found to be independent of foundation scale.

2. Uplift coefficients determined from both Ø and D/B ratio provided superior predictions in the compact and dense density ranges to coefficients determined from Ø alone.

3. Based on a limited comparison, the current formulations of the cylindrical shear model provide more accurate and reliable predictions than the truncated cone or the curve shear surface model.

4. No single theory provides the most accurate predictions in the three density ranges (loose, compact and dense).

5. The best accuracy for one theory across all density ranges is obtained using Ko (1985) followed closely by Ku (1968). If the ranking of Ku (1985) is diminished due to reassessment using independent data, Ku (1968) becomes the superior theory.

6. A combination of theories provides improved forecasting accuracy over the use of a single theory. The use of Ko for loose soil in combination with Ku (1968) for compact and dense soil is recommended for design work.

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TABLE I

Uplift Coefficient Values
Employed in Ontario Hydro

Soil Density	'N' Value	Ku Value
very loose	2-4	0.5
loose	4-10	1.0
compact	10-30	1.3
dense	30-50	1.6
very dense	>50	2.0

TABLE II

Comparability of Median Values of Field and Laboratory Uplift Load Tests Using Notched-Box-and-Whisker Analysis

Field and Laboratory Data Sets With "Equal" Median Values

Theory No	Name	Loose	Compact	Dense
1	Ka	Y	Y	N
2	Ko	Y	Y	N
3	Kp	Y	Y	Y
6	Ku (1973)	Y	Y	Y
7	Ku (1985)	Y	Y	Y
8	Ku (1968)	Y	Y	Y
9	Truncated Cone	Y	N	Y
10	Curved Shear	Y	N	Y

Y = Yes N = No

TABLE III

Statistical Analysis of the Log (Predicted/Actual) Uplift Load Ratio* for Various Uplift Theories in Cohesionless Soil

No	Name	Log Ratio* by Density Range					
		Loose		Compact		Dense	
		Median	Range	Median	Range	Median	Range
1	Ka	-0.3 +/- 0.05	-0.65/0.0	-0.65 +/- 0.05	-1.15/-0.20	-1.1 +/- 0.03	-0.65/-1.40
2	Ko	-0.15 +/- 0.05	-0.45/0.20	-0.4 +/- 0.05	-1.00/ 0.05	-0.9 +/- 0.03	-1.15/-0.55
3	Kp	0.7 +/- 0.05	0.40/1.00	0.4 +/- 0.05	-0.10/ 0.85	0.2 +/- 0.03	-0.10/ 0.50
6	Ku (1973)	0.4 +/- 0.05	0.10/0.70	0.15 +/- 0.05	-0.35/ 0.60	0.0 +/- 0.03	-0.30/ 0.20
7	Ku (1985)	0.25 +/- 0.05	-0.05/0.55	0.20 +/- 0.05	-0 20/ 0.60	0.0 +/- 0.02	-0.20/ 0.20
8	Ku (1968)	0.40 +/- 0.03	0.10/0.70	0.15 +/- 0.05	-0.30/ 0.65	0.0 +/- 0.02	-0.20/ 0.15
9	Trunc. Cone	0.25 +/- 0.10	-0.25/0.85	-0.1 +/- 0.07	-0.60/ 0.40	-0.45 +/- 0.03	-0.70/-0.30
10	Curved Shear	0.7 +/- 0.07	0.25/1.00	0.4 +/- 0.05	-0.10/ 0.85	0.1 +/- 0.03	-0.15/ 0.30

*Note: A value of zero indicates a perfect prediction. A negative value indicates an underprediction. A positive value indicates an overprediction.

†Note: Confidence Limits are quoted after the median value. High and low values are given for range. Outliers are excluded from range values.

TABLE IV

(A) Ranking of Uplift Theories

Rank of Theory	Density Range		
	Loose	Compact	Dense
1	Ko	TC	Ku (1968)
2	Ku (1985)	Ku (1985)	Ku (1985)
3	TC	{ Ku (1968) }	Ku (1973)
4	Ka	{ Ku (1973) }	CS
5	{ Ku (1968) }	{ Kp }	Kp
6	{ Ku (1973) }	CS	TC
7	Kp	Ko	Ko
8	CS	Ka	Ka

Notes: TC = truncated cone
CS = curved shear

{ } indicates ties in ranking
(both theories given higher rank)

(B) Combined Rankings of Uplift Theories

Theory	Rankings				Overall Rank
	Loose	Compact	Dense	Total	
Ka	4	8	8	20	8
Ko	1	7	7	15	5
Kp	7	5	5	17	6
Ku (1973)	5	3	3	11	4
Ku (1985)	2	2	2	6	1
Ku (1968)	5	3	1	9	2
TC	3	1	6	10	3
CS	8	5	4	17	6

TABLE V

Ratio of Predicted to Actual Uplift
Load Capacity for Various Theories in Cohesionless Soil

Theory	Median and Range of Ratio Values					
	Loose		Compact		Dense	
	Median	Range	Median	Range	Median	Range
Ka	0.50	0.22/1.00	0.22	0.07/0.63	0.08	0.04/0.22
Ko	0.71	0.35/1.58	0.40	0.37/1.12	0.13	0.07/0.28
Kp	5.01	2.51/10.0	2.51	0.79/7.08	1.58	0.79/3.16
Ku (1973)	2.51	1.26/5.01	1.41	0.45/1.82	1.00	0.50/1.58
Ku (1985)	1.78	0.89/3.55	1.58	0.82/1.82	1.00	0.63/1.58
Ku (1968)	2.51	1.26/5.01	1.41	0.50/1.92	1.00	0.63/1.41
TC	1.78	0.56/7.08	0.79	0.25/2.51	0.35	0.20/0.50
CS	5.01	1.78/10.0	2.51	0.79/7.08	1.26	0.71/2.00

TABLE VI

Additional Statistical Analyses of Predicted to Actual Uplift Loads for Selected Theories

Theory	Soil Density	Foundation Scale	No of Data Points	Log Ratio Median	Log Ratio Range
TC	compact	laboratory	40	0.0 +/- 0.05	-0.40/0.20
		field	36	0.30 +/- 0.10	-0.60/0.40
CS	compact	laboratory	40	0.43 +/- 0.07	0.10/0.70
		field	36	0.25 +/- 0.07	-0.10/0.80
Ku (1985)	compact	combined	20*	0.37 +/- 0.07	-0.02/0.56
Ku (1985)	dense	combined	41*	0.03 +/- 0.03	-0.15/0.25

Notes: TC - Truncated Cone
CS - Curved Shear
* - reduced data set consisting of data not used in the formulation of Ku (1985) factors

TABLE VII

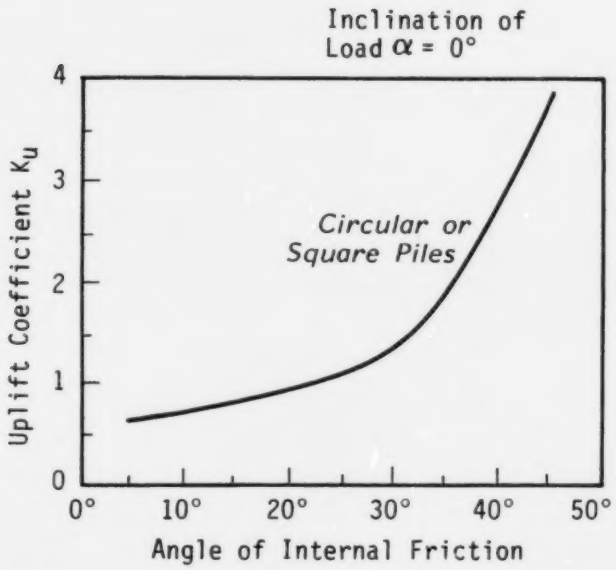
Number of Outliers Found
by Statistical Analysis of Data Sets

Theory	Field Data: Loose	Compact	Dense	Laboratory Data Loose	Compact	Dense
Ka	1	2	0	1	0	1
Ko	1	1	0	1	0	1
Kp	1	3	0	2	0	1
Ku (1973)	1	3	0	2	0	2
Ku (1985)	1	2	0	2	0	4
Ku (1968)	1	3	0	2	0	4
TC	1	0	0	1	0	1
CS	1	0	0	1	1	1
Size of Data Sets	11	36	22	24	40	14

TABLE VIII

Frequency of Occurrence of Outliers

Test Scale	Density Range: Loose — Data Point	Loose — Frequency as Outlier	Compact — Data Point	Compact — Frequency as Outlier	Dense — Data Point	Dense — Frequency as Outlier
Field	3A#6A	8	22B#2	1	none	none
			11H#1	4		
			11H#2	4		
			11K#1	1		
			13B#24b	4		
Labor-atory	19A#1	4	2B#1	1	19A#2	2
	2C#2	8			19A#3	1
					2C#1	4
					54	1
					55	5
					59	1
					60	1



Note: *Digitized K_u versus ϕ (degrees) by the method of least squares (second order) with a goodness of fit, r = 99.1% for circular bored piles subjected to vertical uplift (inclination of load, $\alpha = 0°$)*

$$K_u = f\hat{n}\ (\phi) = 1.1564 - 0.0758\,\phi + 2.8645 \times 10^{-3}\ \phi^2$$

FIGURE 1

K_u COEFFICIENT CHART BY MEYERHOF, (1973) FOR THE CYLINDRICAL SHEAR MODEL

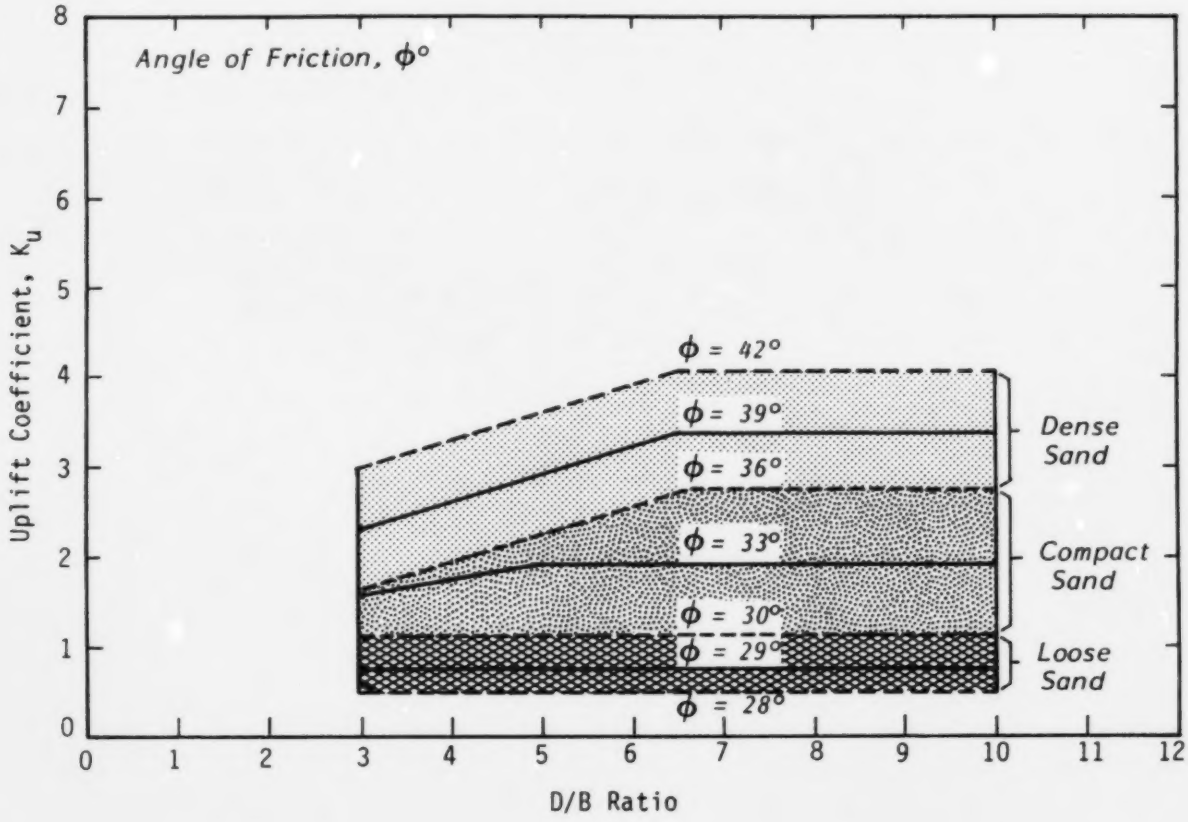
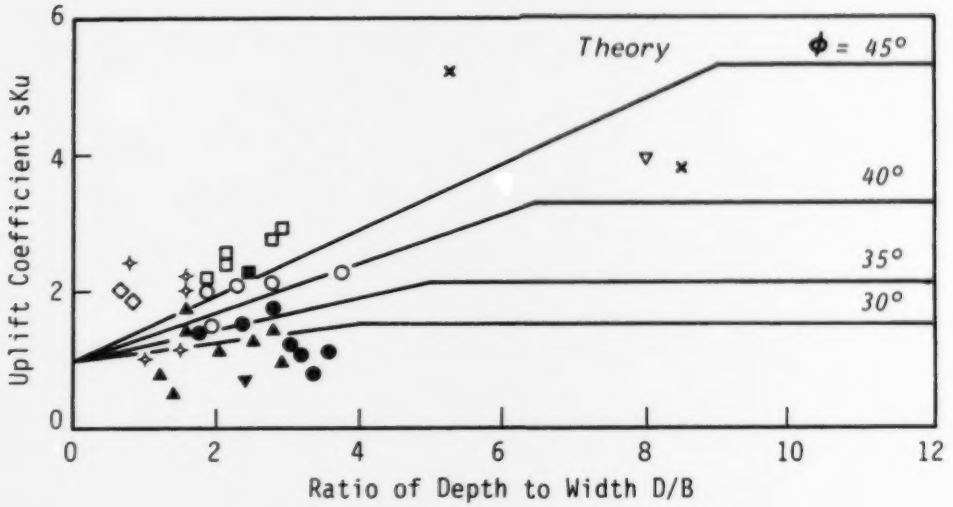


FIGURE 2

K_u COEFFICIENT CHART BY CRAGG ET AL, (1985) FOR THE CYLINDRICAL SHEAR MODEL



Angle of Friction, ϕ degrees
Shape Factor, s

FIGURE 3

K_U COEFFICIENT CHART BY MEYERHOF AND ADAMS (1968) FOR THE CYLINDRICAL SHEAR MODEL

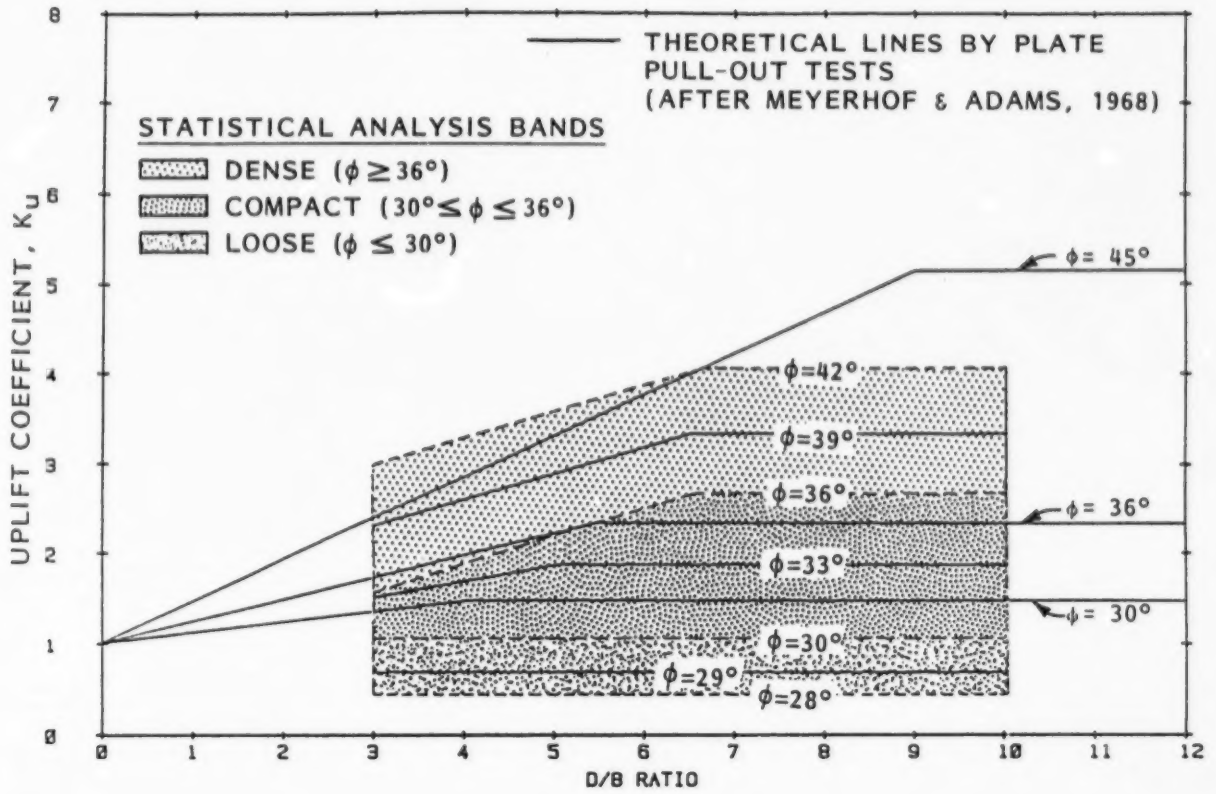
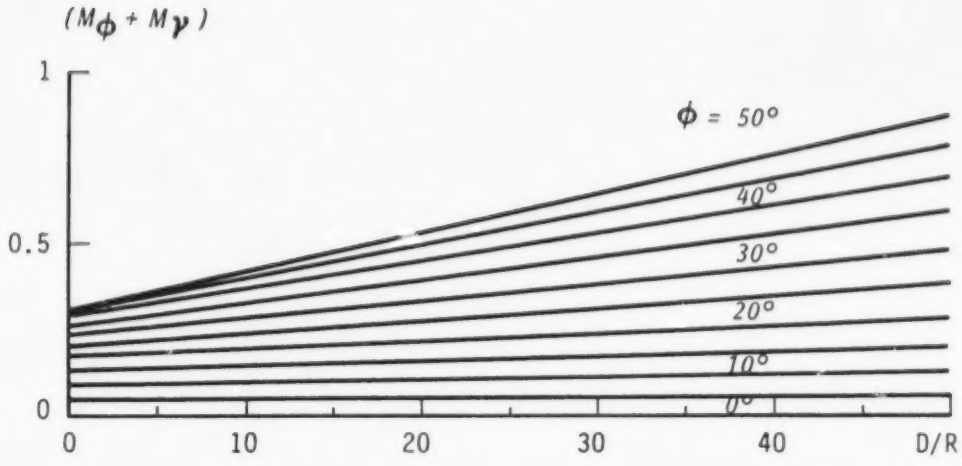


FIGURE 4

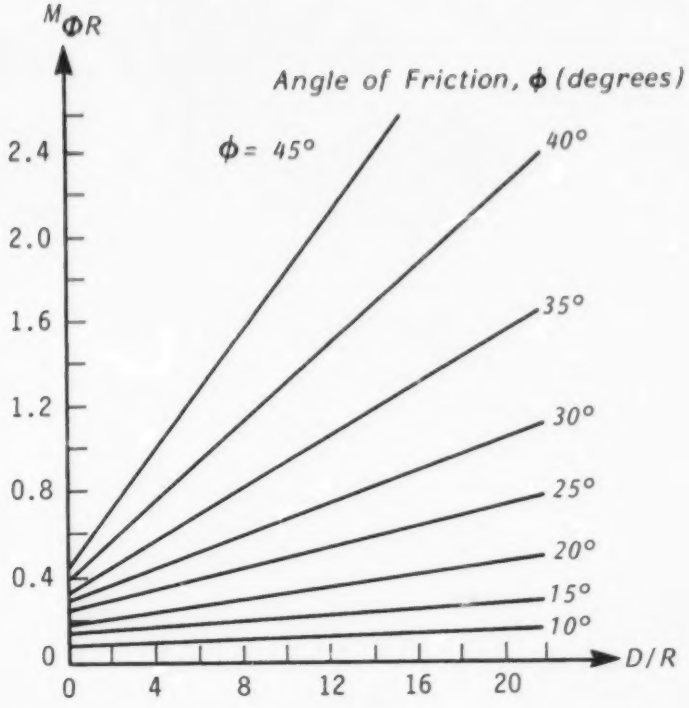
COMPARISON OF COMBINED STATISTICAL UPLIFT COEFFICIENT BANDS WITH K_u THEORY



Embedded Length, D
Radius of Drilled Pier, R
Angle of Friction, ϕ (degrees)

FIGURE 5

**DIMENSIONLESS COEFFICIENT ($M\phi + M\gamma$)
BY BIAREZ AND BARRAUD, (1968)
FOR THE TRUNCATED CONE MODEL**



Embedded Length, D
Radius of Drilled Pier, R

FIGURE 6

COEFFICIENT $M_{\phi R}$ BY TRAN-VO-NHIEM, (1971) FOR THE CURVED SHEAR MODEL

APPENDIX A

STATISTICAL ANALYSIS OF SEPARATE DATA SETS FOR FIELD AND LABORATORY TEST

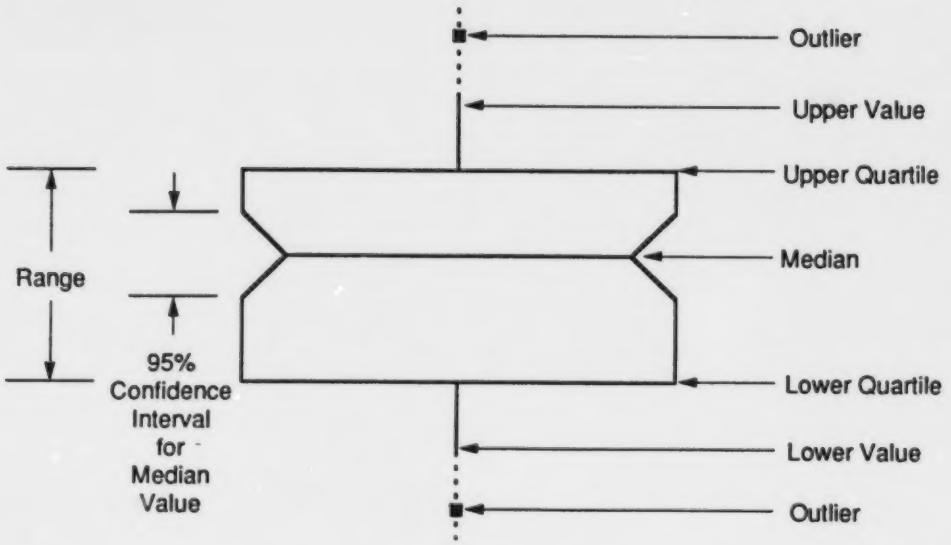
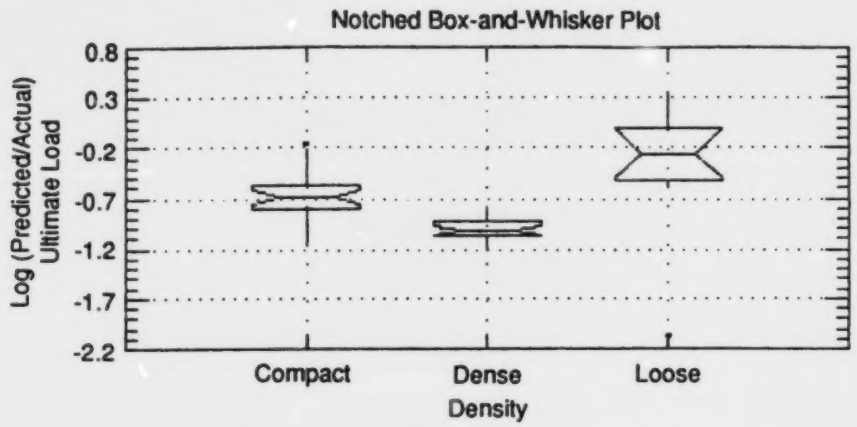
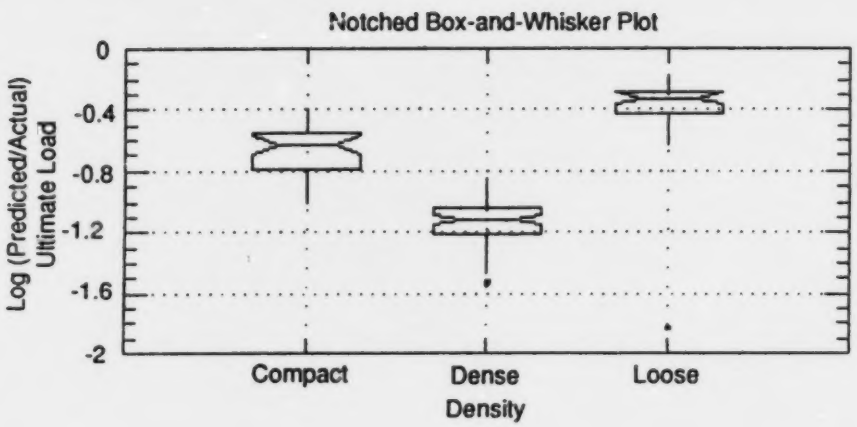


FIGURE A1

GUIDE TO INTERPRETING NOTCHED BOX-AND-WHISKER PLOTS



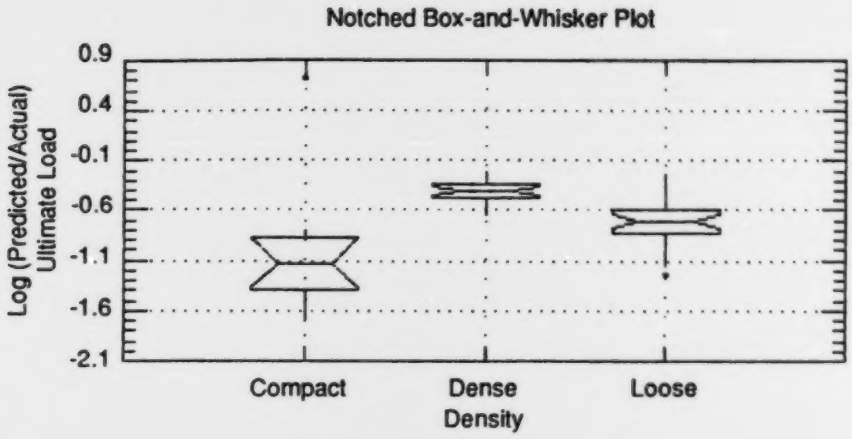
(a) Field Scale Foundation Load Tests



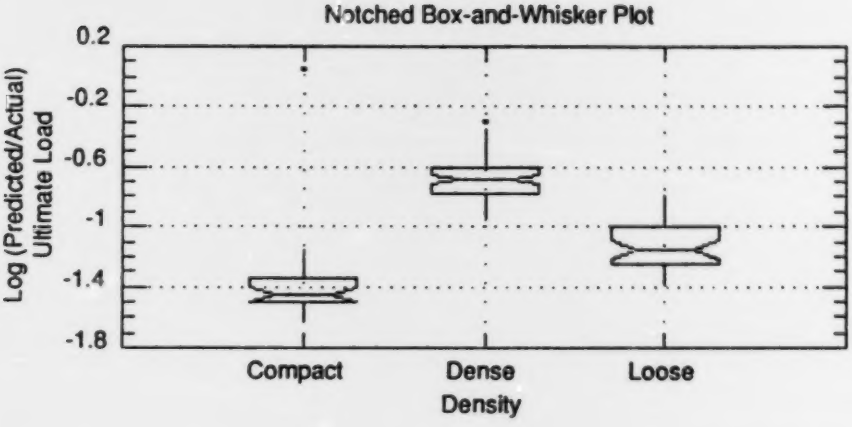
(b) Laboratory Scale Foundation Load Tests

FIGURE A2

STATISTICAL ANALYSIS OF Ka THEORY



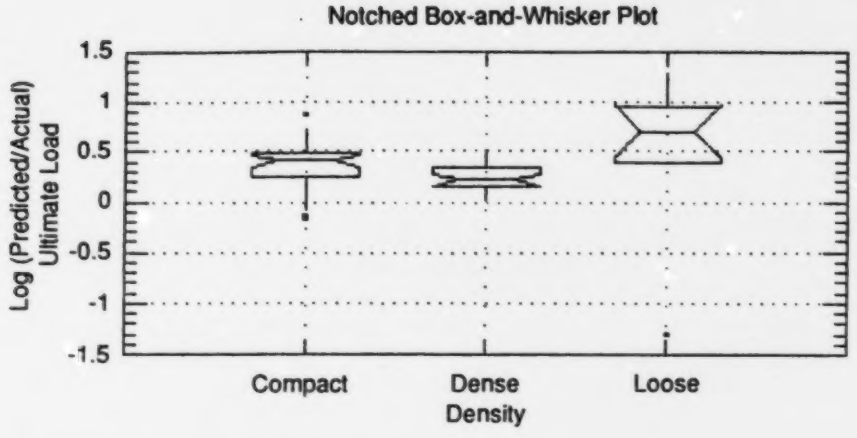
(a) Field Scale Foundation Load Tests



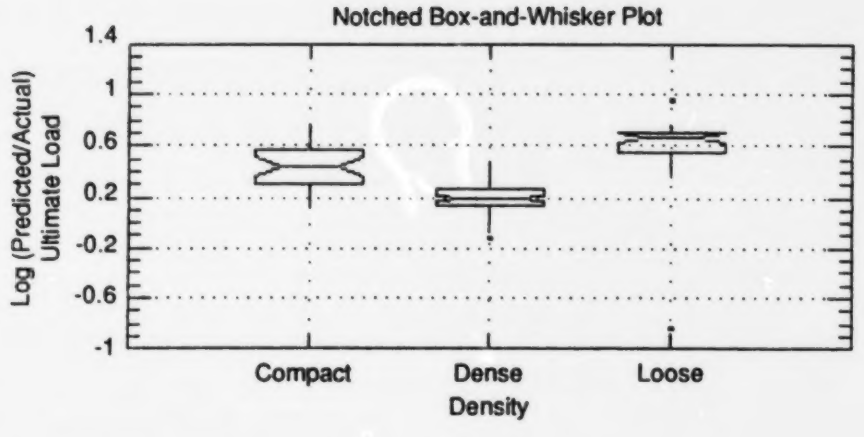
(b) Laboratory Scale Foundation Load Tests

FIGURE A3

STATISTICAL ANALYSIS OF Ko THEORY



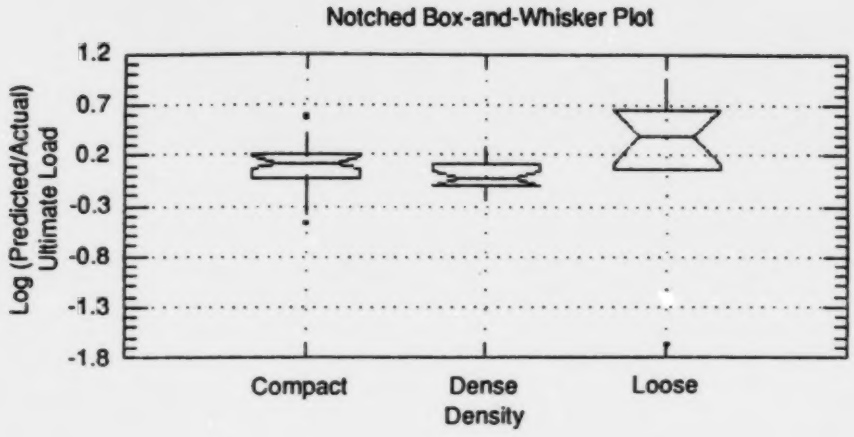
(a) Field Scale Foundation Load Tests



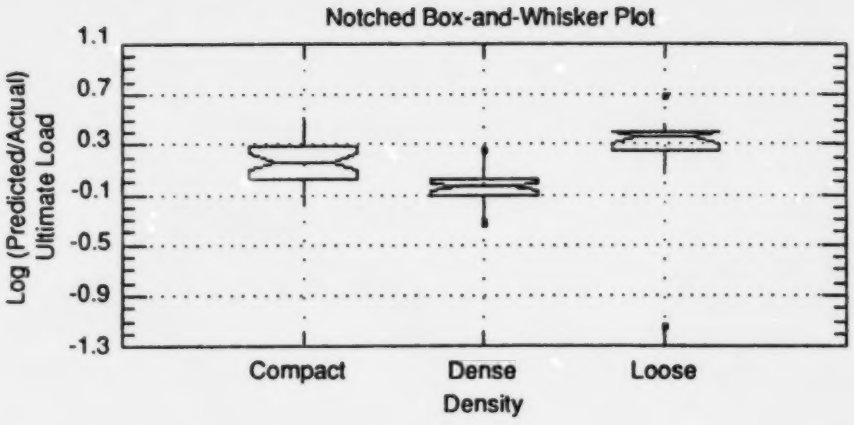
(b) Laboratory Scale Foundation Load Tests

FIGURE A4

STATISTICAL ANALYSIS OF Kp THEORY



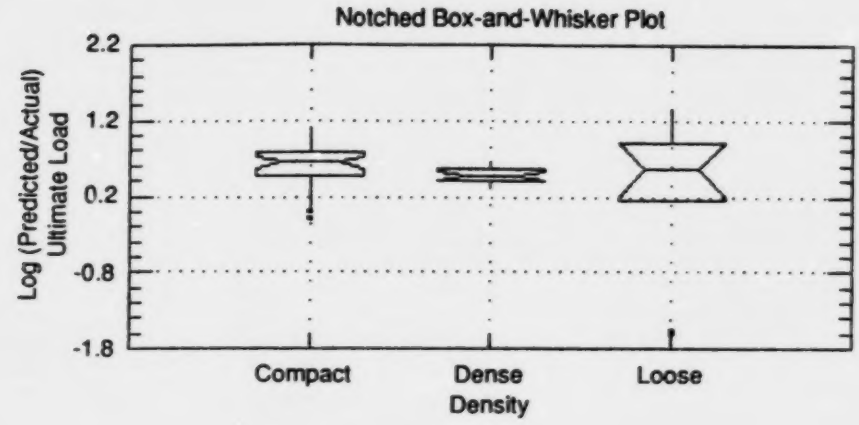
(a) Field Scale Foundation Load Tests



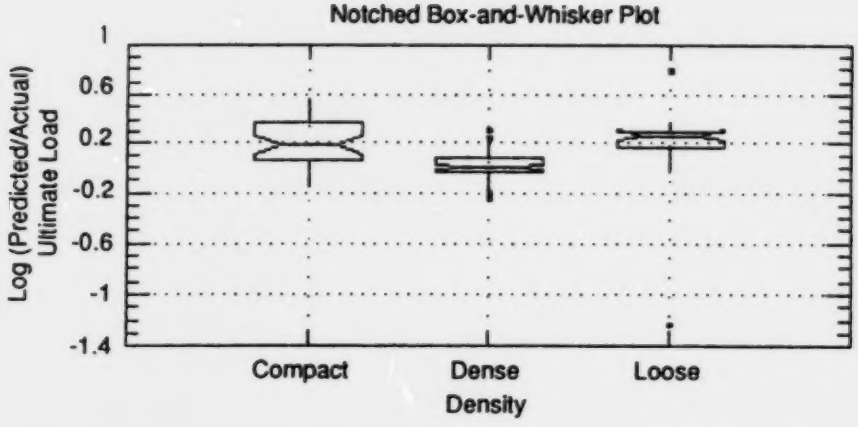
(b) Laboratory Scale Foundation Load Tests

FIGURE A5

STATISTICAL ANALYSIS OF Ku (1973) THEORY



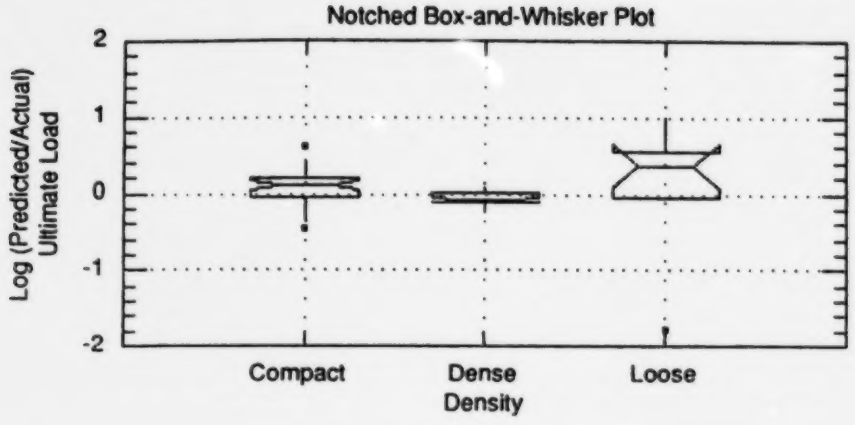
(a) Field Scale Foundation Uplift Tests



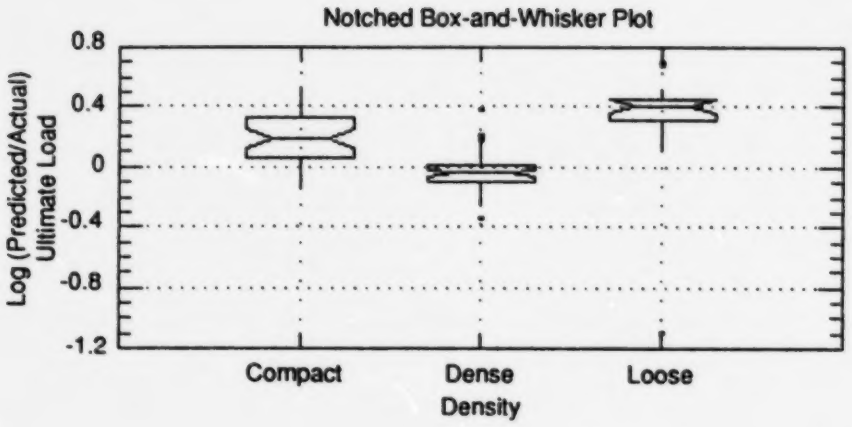
(b) Laboratory Scale Foundation Uplift Tests

FIGURE A6

STATISTICAL ANALYSIS OF Ku (1985) THEORY



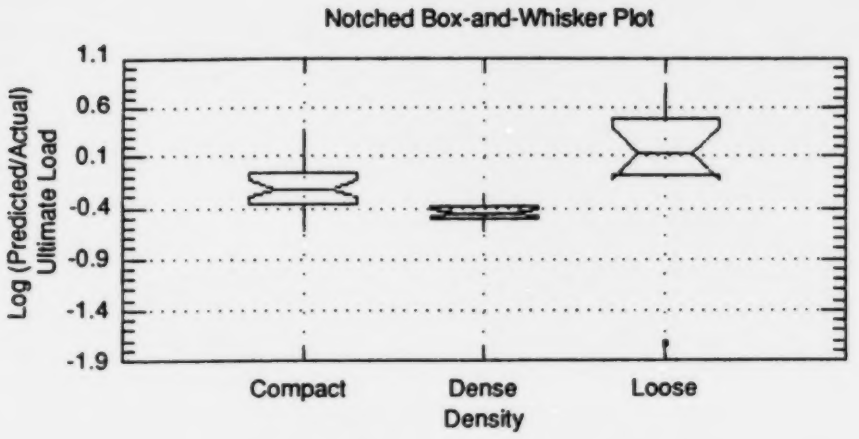
(a) Field Scale Foundation Load Tests



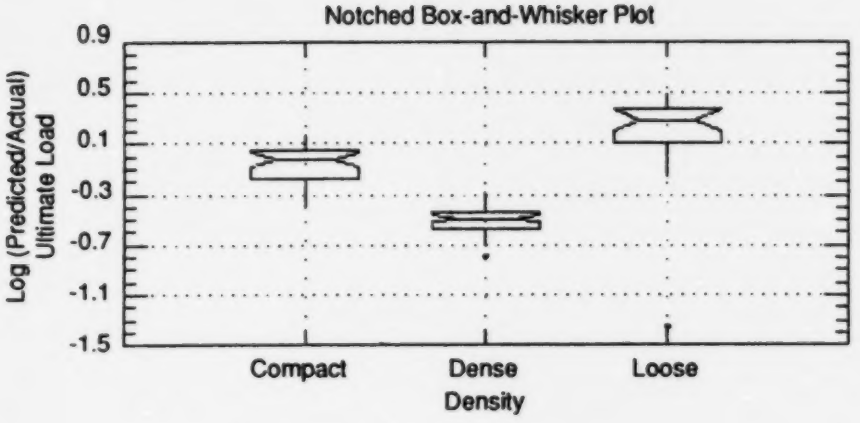
(b) Laboratory Scale Foundation Load Tests

FIGURE A7

STATISTICAL ANALYSIS OF Ku (1968) THEORY



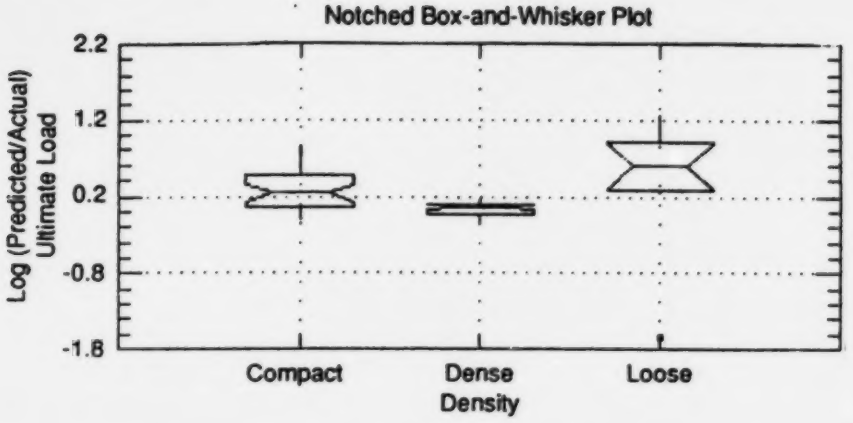
(a) Field Scale Foundation Uplift Tests



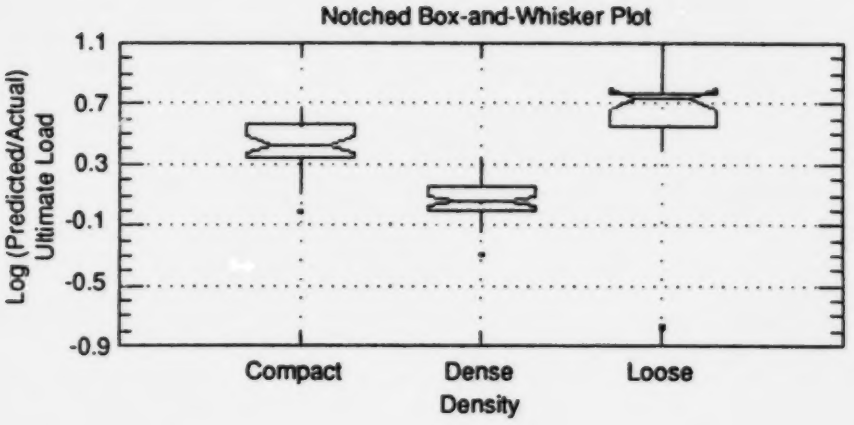
(b) Laboratory Scale Foundation Uplift Tests

FIGURE A8

STATISTICAL ANALYSIS OF TRUNCATED CONE THEORY



(a) Field Scale Foundation Uplift Tests



(b) Laboratory Scale Foundation Uplift Tests

FIGURE A9

STATISTICAL ANALYSIS OF CURVED SHEAR THEORY

APPENDIX B

STATISTICAL ANALYSIS OF COMBINED (LABORATORY AND FIELD SCALE) DATA SETS OF UPLIFT LOAD TESTS

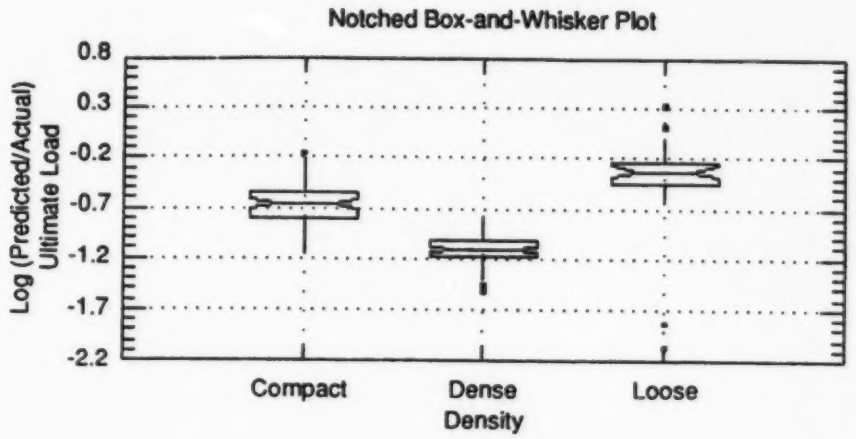


FIGURE B1

STATISTICAL ANALYSIS OF Ka THEORY

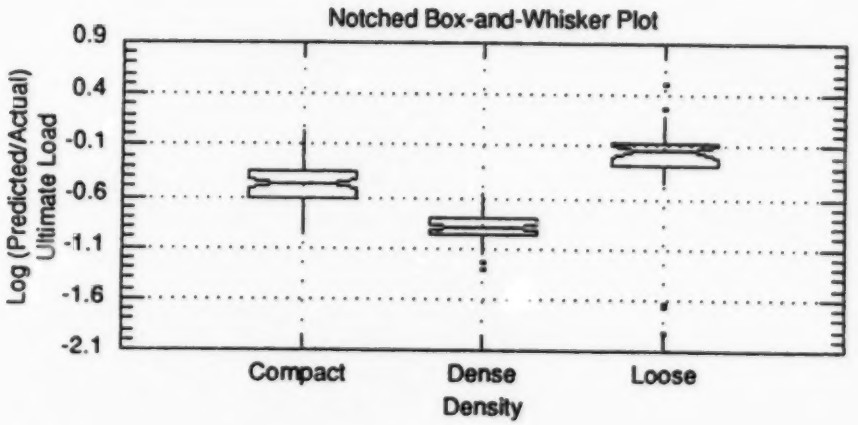


FIGURE B2

STATISTICAL ANALYSIS OF Ko THEORY

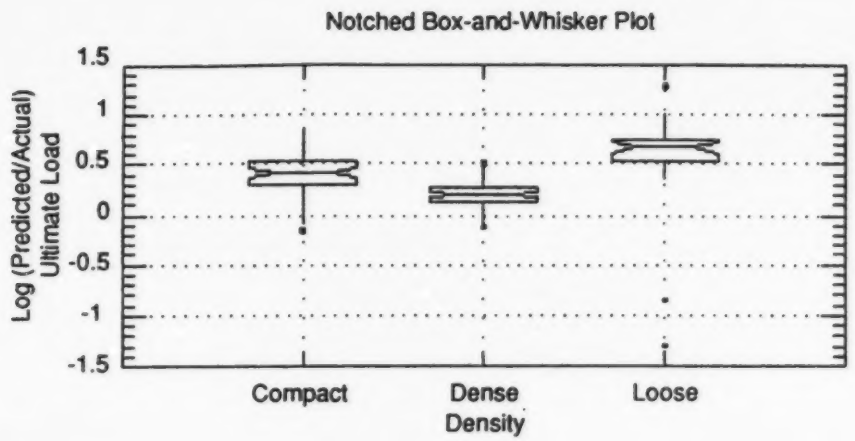


FIGURE B3

STATISTICAL ANALYSIS OF Kp THEORY

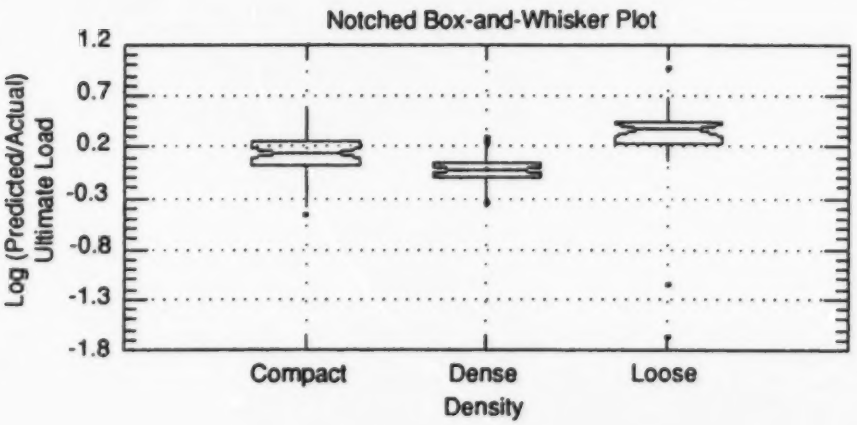


FIGURE B4

STATISTICAL ANALYSIS OF K (1973) THEORY

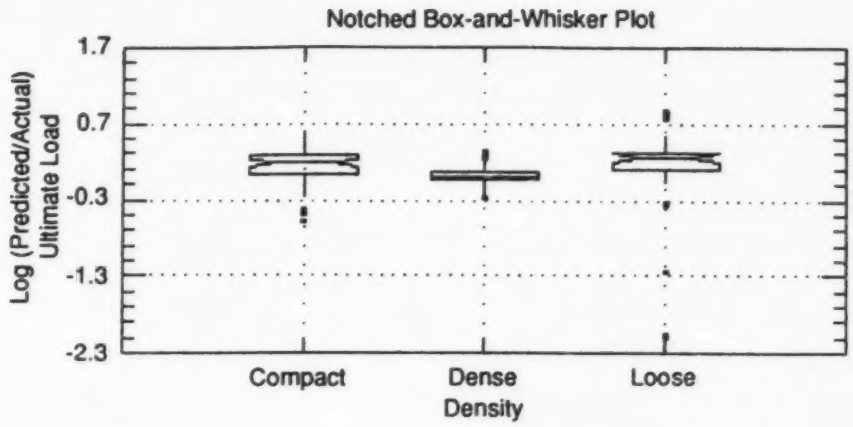


FIGURE B5

STATISTICAL DESIGN OF Ku (1985) THEORY

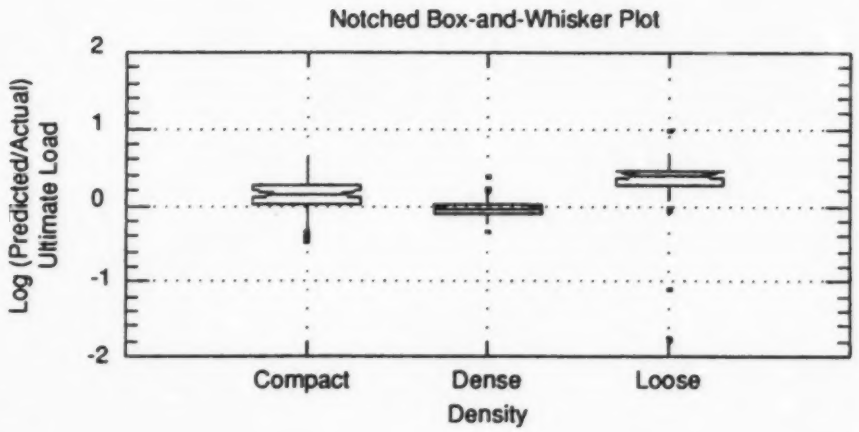


FIGURE B6

STATISTICAL ANALYSIS OF Ku (1968) THEORY

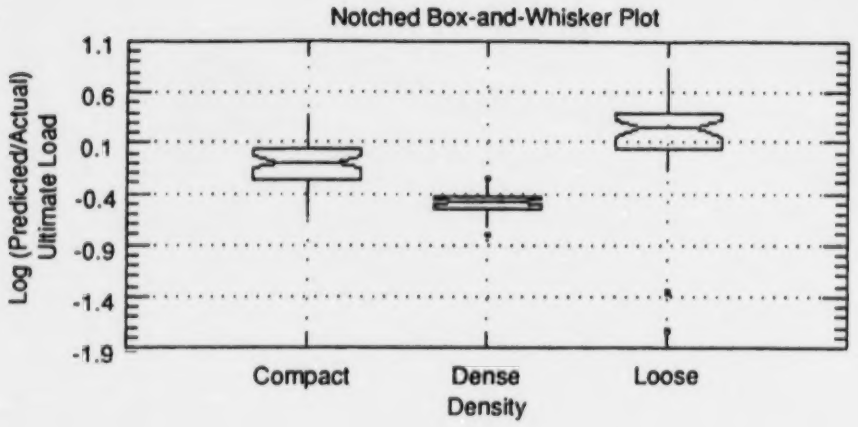


FIGURE B7

STATISTICAL DESIGN OF TRUNCATED CONE THEORY

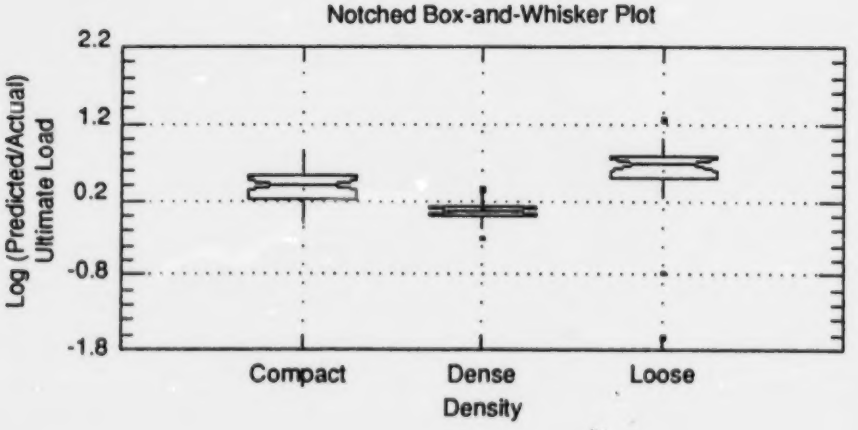


FIGURE B8

STATISTICAL ANALYSIS OF CURVED SHEAR THEORY

APPENDIX C

STATISTICAL ANALYSIS USING REDUCED AMOUNT OF DATA IN COMBINED (LABORATORY AND FIELD SCALE) DATA SETS OF UPLIFT LOAD TESTS

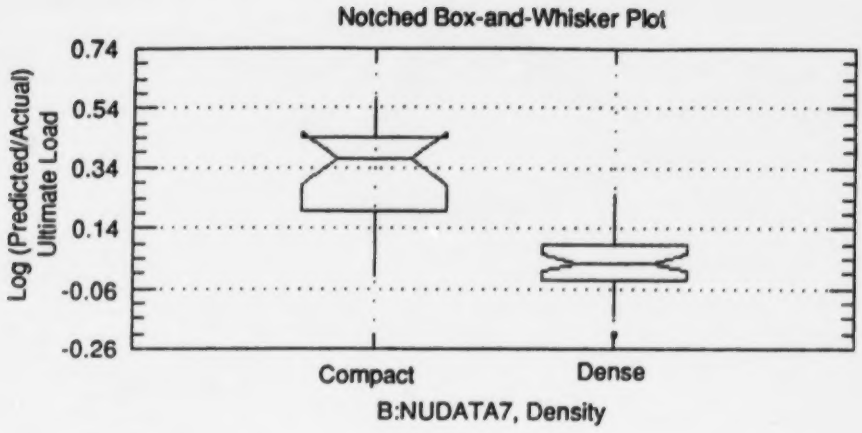


FIGURE C1

REVISED STATISTICAL ANALYSIS OF Ku (1985) THEORY